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# SIR THOMAS WRIGHTSON'S THEORY OF HEARING[1]

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The Helmholtz theory of audition, in spite of Ebbinghaus' gallant effort to save it, seems to have sunk beyond recovery. The historian of science must always regard it with admiration, since for combined range and detail and directness of correlation it is still without a rival; and indeed, as model of what a theory 'ought' to be, it will probably figure for many years to come—with the more or less emphatic warning that it need not be believed—in textbooks of physiology and psychology. Helmholtz himself, eminent in physiology and yet more eminent in mathematics and physics, was (we used to think) a living guarantee of the rightness of his theory, a physical theory of a mechanical organ: we might mistrust his theory of vision, but we could trust the physiology and physics of the *Tonempfindungen*. Little by little, however, acceptance has given way to doubt; the modern physicist will not be pinned down to Helmholtz' 'nothing but' sympathetic vibration, and objects positively that sympathetic vibration is put out of court by the dimensions and structure of the internal ear; the

[1] An Enquiry into the Analytical Mechanism of the Internal Ear, by Sir Thomas Wrightson, Bart., Memb. Inst. C. E., with an Appendix on the Anatomy of the Parts Concerned by Arthur Keith, M. D., F. R. S. London, Macmillan & Co., Ltd., 1918. Pp. xi.+155+Appendix (156-254)+9 Plates. See also the account in *Proc. Roy. Soc. Med.*, 12, 1919, Otology Sect., 80-94; and the discussion by Bayliss, Keith, Wrightson, Perrett and Rayleigh, *Nature,* 102, 1918, 124f., 164f., 184f., 225, 263f., 304, 325.

modern physiologist looks in vain for Helmholtz' resonators; and the modern psychologist, oppressed by the number and complexity of his facts of observation, wishes to clean his slate of theory and to start afresh from a thoroughgoing study of the sense-organ, biological, anatomical and physiological.

Meantime, of course, theories flourish, and must be considered as they come. The theory set forth in the book before us is that of an engineer, who approaches the ear "as a piece of working machinery." First conceived as long ago as 1876, it has now been wrought out in detail; and the author has sought to clinch its application by calling in the aid of an anatomist. The combination of forces is unusual; the disregard of psychology is—to a psychologist—refreshing; and we begin to read with a hopeful curiosity. May not this frankly teleological attitude toward the sense-organ, as a machine in being, put us all, physiologists and psychologists alike, on the right track ?

Whether or not this hope is eventually to be fulfilled, we soon discover that the writer has not troubled to make things easy for us. His style appears at first to be clear and simple, but in fact it is neither the one nor the other. His physical terminology, in particular, is at best misleading and at worst incorrect. The terms pressure, force, power, work, and momentum are used loosely despite their precise physical meanings;[2] and discussion that begins thus inexactly ends, as it must, in positive error.[3] Moreover, the exposition of the theory is annoyingly unsystematic. We find digressions, repetitions that are sometimes almost verbal, and a general absence of the coordination that might have been effected by literary organization or by cross-referencing. Again and again the reader fails to divine the author's purpose; when is he seeking an account of the analytical mechanics of the internal ear, and when the establishment of a theory of hearing? Much of the description belongs only to the former context, and much of the discussion only to the latter, and the resulting confusion has to be cleared up by re-reading.

The burden of comprehension is thus heavier than it need

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[2] *Cf.*, *e. g.*, the confusion of work and power, pp. 134 f. The reader will find plentiful instances of a like kind.

[3] Consider *e. g.*, the application of the energetic principle of conservation to forces which should be dealt with as equilibrated, and the consequent discovery of a supposititious residual force effective in the cochlea: p. 94, lines 9 ff.

be. We do not desire, however, to make too much of this criticism. The book is a war-book; the preface is dated February, 1917; and the writer may have had scant leisure for polishing his material. The looseness of terminology is a more serious matter. We proceed to show, in a number of instances, that it means a fatal looseness of thought.

1. In his preliminary analysis of compound wave-forms [4] Wrightson shows that, if the simple wave-forms be represented by straight lines forming a series of V's, the algebraic addition of two simple wave-forms respectively of frequency $x$ and frequency $y$ will give a compound wave-form, which has $(x+y)$ and also $(x—y)$ approximately equidistant crossing-points (intersections of wave-form with horizontal axis). These two periodic series show no significant interrelation. Wrightson attributes to the $(x+y)$ series the summational tone, and to the $(x—y)$ series the differential tone. The correlation is, however, unsatisfactory. It is to be presumed—and Wrightson seems to imply—that similar properties in the wave-form underlie both simple tones and combinational tones. But the tone $x$ is heard for a wave-form that has $2x$ crossing-points (a complete wave crosses the axis twice); and a tone $y$ is heard for a wave with $2y$ crossing-points. If $(x+y)$ be the summational tone, then it might be expected to have $2(x+y)$ crossing-points. The differential, in like manner, should be conditioned upon $2(x—y)$ crossing-points. Wrightson's $(x+y)$ and $(x—y)$ are each of them an octave too low. The $(x+y)$ crossing-points, moreover, represent an average frequency, and not a sum.

2. This discussion of triangular wave-forms is preliminary. We come presently to the compounding of tones of sine-form. Here we learn that, if we regard every crest, hollow, and crossing-point as an " impulse point," we have possessed ourselves of a key to an understanding of the ear's analysis of compound waves. More concretely: if we build up a compound wave-form by the algebraic summation of sinusoidal components, and note in the complex form the positions of all crests, hollows, and crossing-points, we discover that a great many of these critical points are separated by distances which are approximately the same as the wave-length of one component; that many other pairs of points are separated approximately by the wave-length of the other component; and that

[4] Pp. 12-17; Plate I.

still other points show separations which correspond with the summational tone or the differential tone. This discovery justifies, we are told, the initial assumption that crossing-points, crests, and hollows all function in the same way.

A little reflection, however, raises the question why Wrightson, in these graphical experiments, should wish to find the *wave-lengths* of the components reproduced in the compound. In a simple tone there are two crossing-points, one crest, and one hollow, in every single wave; four impulse points in all. A tone of $x$ vibrations per sec. has $4x$ impulses within the second. It would seem, therefore, that Wrightson should have made his analysis of the compound wave by seeking out recurrences of the quarter wave-length rather than of the wave-length. Whether an analysis with respect to quarter-waves would fail we can not tell. The original curves in the publication of 1907,[5] which unfortunately is not at present available to us, must be analyzed again (as they were originally) by a cut-and-try method.

3. There are more difficulties of the same order, but they appear at higher levels of the argument. We must observe next a fundamental assumption of a different kind.

Wrightson, in his analysis of the hydraulics of the inner ear, ordinarily uses hydrostatic and not hydrodynamic principles. He employs the terms power, work, and momentum; but the dynamic principles that these terms imply do not dominate the discussion. There is no reference to the inertia of the moving parts, although the difference in phase of the curve of air-pressure and the curve of air-displacement[6] is a matter of inertia. Wrightson draws the analogy to the steam-engine as if the work transmitted to the hair-cells were the vehicle of sensation.[7] The engineer's interest in the steam-engine, however, lies ultimately, not in its work, but in its power. Power is rate of doing work; and both the frequency and the amplitude of a tone must be considered if mechanical power is the key to hearing. An engineer determines mean effective pressure by putting a steam-indicator on the steam-cylinder, just as Wrightson wishes might be done with the inner ear;[8] but the engineer does not then forget to measure the speed of the shaft.

The substitution of static for dynamic principles begins in Wrightson's argument when we pass from the sounding air to

[5] P. 31.
[6] P. 76.
[7] Pp. 94, 134.
[8] Pp. 1, 134 f.

the mechanical system of the middle and inner ears [9]. Wrightson shows the waves of pressure and displacement separated in the air,—a dynamical separation. He then notes that the stapes moves as the result of air-pressure upon it, and assumes that it will therefore move *with* the air-pressure.[10] In a series of hydrostatic equilibria it would so move; the position of the stapes would be a function of the pressure upon it. But hydrodynamically there would be a lag due to inertia. An imponderable stapes in air would move with the ponderable air and not with the pressure of the air. An actual stapes weighted by a mass of liquid would similarly be out of phase with air-pressure.

In another passage we read: " As liquid pressure in a closed vessel exerts itself equally in every direction the unit pressure at any one moment which enters the cochlea is not affected by the shape of the vessel." [11] This misstatement is symptomatic of the entire hydraulic account of the inner ear. The law of equal pressures is the hydrostatic law. Engineers make use in the Venturi meter of the fact that pressures are not everywhere equal within a moving liquid, and that the shape of the containing vessel determines the rate of movement and thus the pressure.

The fundamental principle of hydrostatics is the equilibration of forces. Every body is considered in equilibrium and the sum of the forces acting upon it equated to zero. This mode of working is not adequate in hydrodynamics; but it is the mode that Wrightson uses;[12] and it makes difficulty later on.

If it is argued that the masses involved are so minute that their inertia is neglible, we reply that the masses are not disappearingly small and that their rates of motion are very great. Moreover, we must remember that Wrightson's theory stands or falls with the assumption that the ordinary principles of mechanics apply.

4. If we grant the dynamical nature of the problem, we must ask why Wrightson supposes that the movement within the inner ear is a mass-displacement of the lymph and not a transmission of sound-waves, since water does in fact conduct sound. Bayliss has already raised this question.[12a] Wrightson's answer is misleading. He holds that the lymph is " (at

[9] P. 76.
[10] Fig. 30.
[11] P. 47.
[12] *Cf.* pp. 80-87, esp. 83 ff., 86; 124.
[12a] W. M. Bayliss, *Nature,* 102, 1918, 124, 263.

the minute pressures dealt with) inelastic and incompressible, and will therefore be moved instantaneously in the passages of the cochlea."[13] He quotes Helmholtz as authority.[14] He is especially insistent that a liquid is inelastic.[15]

As a matter of fact, however, liquids are not absolutely incompressible and they are highly elastic. Elasticity and compressibility are *inversely* related;[16] a liquid is highly elastic because it is relatively incompressible. The true answer to Bayliss' question has been given by Rayleigh; the cochlea is so short with respect to the wave-lengths of ordinary audible tones that there could be very little difference of phase between the pressures at the oval window and at the round window, and transmission would therefore be practically instantaneous.[17]

5. We may include as a separate item in this list the fact noted above, that the curve of displacement of the stapes can not be, as Wrightson believes,[18] synchronous with the curve of air-pressure. His assumption that the two are synchronous sets the stage for the difficulties of all the discussion that follows.[19] Here the neglect of the dynamic principle is especially unfortunate because of the critical part played by the conclusion.

6. Thus we come to the most important part of the theory, the demonstration that every complete wave of pressure in the air, consisting of a positive and a negative phase, is correlated with the two positive phases and two negative phases of a pressure-curve within the cochlea. The reader must refer to Wrightson's book for the details of the argument.[20]

If we take Wrightson at his own level of exposition, we are at once entitled to object to the development of Fig. 34. Here (by analogy to Fig. 33) " C" must be the mid-position and " B " the extreme position of the stapes. The generating time-circle is struck with " B " as a center; so that the stapes, in moving from " C " to " B," is shown as starting from rest at " C " and moving faster and faster until it reaches " B," where it changes direction and moves back on the return

[13] Pp. vii, 80, 90, 115.

[14] Notes on pp. 56, 74; p. 130; and *Nature,* 102, 184.

[15] Pp. vii, 77, 121, 128, 130.

[16] Elasticity=stress/strain=compressing force/amount of compression. The less the compression produced by a given force the greater the elasticity. *Cf.* A. Winkelmann, *Handbuch der Physik,* I, 1906, 497-503.

[17] *Nature,* 102, 304.

[18] P. 76.

[19] Pp. 76-96.

[20] Pp. 80-84, Fig. 34 and Plate V.

stroke. Such a movement of the stapes is, however, manifestly impossible. The stapes can not reverse the direction of its movement at maximal speed; it must, like any other object in pendular motion, slow down and pass through rest at the moment of change. Moreover, Wrightson elsewhere notes that it halts in the extreme position.[21] Yet Fig. 34 shows it moving over a maximal space in the last increment of time!

The remedy is simple. The time-circle of Fig. 34 must be struck with its center at "C." (Where else indeed should the center of the generating circle for simple harmonic motion be placed than at the center, "C", of the total displacement?) The stapes, like a swing, moves fastest at its mid-position "C," slows down, and reverses direction at "B." It does not, as Wrightson maintains, stop momentarily at "C" as well as at "B." What, we wonder, has led Wrightson to believe in this arrest of motion at "C"? The examples of reciprocating motion with which the engineer is familiar furnish no ground for the belief. It can not arise in consequence of the invocation of Hooke's law; for it is formulated prior to the mention of Hooke's law, in order that the combined effect of Hooke's law and the twofold arrest may be worked out. Probably the error springs from the assumption that stapedial displacement is an immediate function of pressure (the fifth point mentioned above); for the pressure is zero in the mid-position, and Wrightson seems to think that the resultant velocity must also be zero. He forgets, it appears, that a swing moves fastest in its mid-position, when the effective component of gravity is zero.

If we dissent from Wrightson's reasoning, and consider the stapes as moving fastest in the mid-position, we must strike the generating circle about "C." The curve of elastic resistance, as thus developed, becomes a sine curve and not a versine. If we then take the difference between the imposed pressure (sine curve) and the opposing elastic pressure (now shown to be also a sine curve)[22] we get as the curve of transmitted pressure, not Wrightson's two positive phases followed by two negative phases,[23] but zero pressure. This is exactly the result which could have been foreseen. We are dealing implicitly with hydrostatics and forces in equilibrium. Under Hooke's law and these assumptions the elastic membranes will stretch until they give back a reacting force equal to the impressing

[21] *Cf.* pp. 87, 121, 142.
[22] *Cf.* Plate V.
[23] The red curve of Plate V.

force. Thus we demonstrate Newton's third law. Action and reaction are discovered equal!

It stands to reason that no pressure could be transmitted through the *fenestra ovalis* if there were nothing beyond to press against,—granted always that the pressures due to inertia and change of velocity are, with Wrightson, left out of account. But in point of fact there are elastic pressures arising within the inner ear. Wrightson admits them,[24] but regards them as neglible in comparison with the tensions of the tensor tympani and the stapedius. They are the elastic pressures from Reissner's membrane, the tectorial membrane, the basilar membrane, and the *fenestra rotunda,* all of which are displaced with the stapes. Far from being neglible, they are the determinants of internal pressure within the cochlea, which is of their order of magnitude. The pressure in any canal is the pressure necessary to displace the membranes lying beyond it. In the cochlear duct, the hydrostatic pressure would be atmospheric pressure *plus* the pressures due to the distension of the basilar membrane and round window. In the tympanic canal the pressure would be atmospheric pressure *plus* the pressure from the round window only. In a dynamic system the pressures would depend in addition upon the rate of motion and the inertia of the cochlear lymph. In any case, however, they would be approximately sinusoidal, and they must be accounted for by conditions within the cochlea, and not as a residual left over from the operation of the mechanism of the middle ear.[25]

7. The central feature of the Wrightson theory is this complete cessation of pressure and motion at four points within the complete period.[26] These critical points are points of zero pressure in the doubled cochlear wave, and they are correlated with the crests, hollows, and crossing-points of the air-wave. Thus we get an inkling of the significance of impulse points in Wrightson's analysis of mechanically compounded curves in the earlier part of his book.[27] We saw, however, that his analysis is faulty because the four-fold total wave, instead of the significant quarter wave-length, is laid off among the

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[24] Pp. 144, 154.

[25] This whole discussion of a residual pressure which is delivered to the elastic membranes and not taken up by them, so that something remains over for further use, sounds very much as if work or energy were in question. For there is no principle of the conservation of pressure! But the main argument applies to pressure; and if Wrightson shifts his meanings without changing his words, the reader can not be held responsible.

[26] Pp. 87, 121, 124, 142, 196, 212, 218.

[27] Pp. 26-35, 60-71.

impulse points of the compound curve. We see here that the mechanical significance of the impulse points fails of establishment. We still can not deny the graphical coincidences of the curves, but we may deny that they have brought us far toward an understanding of hearing.

8. If the cochlear curve of pressure is not doubled, there is no "subjective octave."[28] "Subjectively," *i. e.* in the cochlea, there are just as many crests and troughs and crossing-points as there are "objectively" at the tympanic membrane. But even if the cochlear curve is doubled, as Wrightson would have it, we should not expect to find, as he does, that both the objective tone and its subjective octave are effective for hearing.[29] Wrightson seems to assert that for the tone $m$ the cochlea receives impulses corresponding both with $m$ and with $2m$. Moreover, the subject is expected to hear both $m$ and $2m$ together; at least both $m$ and $2m$ are held to be simultaneously effective in the production of combinational tones. This argument is untenable both in fact and in logic: one does not hear in a pure tone its octave, and one does not eat one's cake and still have it. If the cochlear determinant of tones is doubled, then it can not still be single.

9. With the subjective octave goes Wrightson's explanation of all differential tones but the first.[30] One of his differential tones, $(2m—n)$, does not exist, to our knowledge, for any other theory. The first differential is supposedly grounded in the nature of the compounded curves; but we have seen that the preliminary discussion indicated a differential tone an octave too low, and that subsequent discussion was based upon an improper unit. Hence there is as yet little promise of a revised theory of differential tones.

10. The summational tone is in no better case. Wrightson does not condition it upon the subjective octave, though he might have done so had he allowed differential tones of the second order.[31] The summational tone goes the way of the first differential tone; the arguments in its favor that we have noted in our first and second paragraphs are not convincing. Even were they final, they would prove embarrassing; since they would indicate that the summational tone is a prominent component of all fusions; whereas, introspectively, the summational tone is weak. Wrightson concludes with an attempt at

[28] P. 143.
[29] Pp. 147 f.
[30] Pp. 148 f.
[31] *Cf.* W. Wundt: *Physiol. Psych.*, i., 1893, 465.

diagrammatic establishment of the summational tone;[32] but he fails here for the reason that we have given, and for another reason that we must now mention.

11. The final account of the mode of treatment of the cochlear pressure-curves[33] raises new queries. Wrightson obtains a cochlear curve for a compound of two tones by adding algebraically the cochlear curves of both tones. The result is not what we should expect (*cf.* Plate VIII); since the sum of the cochlear curves of the separate tones is not what the cochlear curve of the sum of the separate tones would seem to be. Presumably, since compounding actually occurs in the air, we should first compound the sine curves, and then find a cochlear function. Be this as it may, Wrightson now proceeds by the cut-and-try method to lay off between impulse points the wave-lengths of the separate generators, of the differential tones, and of the summational tone; and *he takes as impulse points the crests, hollows, and crossing-points of the cochlear wave.* Up to this point we had thought that the reason for calling the crests, hollows, and crossing-points of the air-wave " impulse points " is their correlation with the points of supposedly zero-pressure of the doubled cochlear wave. Now we are suddenly confronted in a simple wave with *eight* impulse points; for in a single period the cochlear wave can have four crossing-points, two hollows, and two crests. Still, however, this gratuitous doubling of the number of impulse points results in graphic concidences! It is strange that the theory, if we take the diagrams at their face value, should thus insist on proving itself. Moreover, there is something disconcerting about a theory that will come right on any assumption. We ask in bewilderment *what* it is that the theory theorizes,—whether the facts that it is supposed to be concerned with, or some irrelevant character of graphic forms.

It is a pleasure to turn from criticism to appreciation. And if the summary statement of our debt to Wrightson is shorter than the catalogue of objections to his theory, that is only because it may be set down without comment or argument. The points to which we desire to call attention lie for the most part at the level of observation,—naturally, since the conclusions at the higher level of the theory are dependent upon reasoning to which we have been obliged to take exception.

1. We must note in the first place Wrightson's discovery

[32] Pp. 151 f. and Plate IX.
[33] Pp. 150-152 and Plates VIII, IX.

that the compounding of two periodic V-shaped wave-forms of frequencies $x$ and $y$ gives a compound curve of $(x+y)$ and of $(x-y)$ intermediate and approximately equidistant crossing-points; and that this characteristic of compounding is independent of the phase-relation of the components.[34] Wrightson apparently made his discovery by an inspection of plotted samples, and without having the ultimate form of his theory in mind. The cases presented in Plate I are convincing samples: there seems to be no reason why the validity of the generalization should be doubted. It would be interesting to work over some of the cases accurately, by analytics or graphics, in order to determine the mean variation of the points from exact periodicity and thus to arrive at a definition of the approximation.[35] The meaning of the relation, as we have seen, is not obvious; but it is a novel idea that compound waves may be understood by a study of the occurrence of critical points within them.

2. Wrightson makes a similar discovery in the compounded sine curves, plotted by the ohmograph,[36] the invention of which is in itself a contribution to acoustics. If the hollows, crests, and points of crossing are taken as critical points, the distribution of these critical points shows simple relationships to the component wave-lengths and to the wave-lengths corresponding with the sum and difference of the component frequencies.[37] Again we are reminded of the possibility that we may solve the problem of hearing by reference to a periodic recurrence of critical points, rather than by reference to the total wave-form or the wave-form of the components. Here the analogy of the siren, where the ratio of size of hole to space between holes (wave-form) is much less important than the rate of recurrence, is peculiarly suggestive.[38]

3. The conception of the conditioning of tone on the periodic recurrence of momentary impulses raises the question of the effect of aperiodic impulses. Wrightson finds critical points that are 'aperiodic,' except that they recur at long intervals; for a wave-form compounded of two commensurable components must eventually repeat itself and therefore every point within itself. He regards these additional points of long period as the correlates of noise,[39] and remarks that the

[34] Pp. 12-17 and Plate I.
[35] *Cf.* p. 30.
[36] Pp. 24 f. and Plate III.
[37] Pp. 26-30, 60-77.
[38] Pp. 6-8.
[39] P. 35.

poorer fusions, where the 'aperiodic' points occur more frequently, are the noisier. It is true that the poorer fusions have upon them a greater roughness or *vibrato,* and it is possible that Wrightson provides a key to this introspective fact. If one can hear in a major seventh two tones *and* a *vibrato,* any theory that provides three elements in the compound wave is so far illuminating. We may point out, further, that Wrightson's characterization of the 'aperiodic' recurrences as noise agrees with Jaensch's view, and that both Jaensch's and Wrightson's noises are periodic in a long period.[40]

As with the graphics of wave-form, so with the mechanics of the ear, Wrightson accomplishes more at the level of fact than at that of interpretation. His text and Keith's appendix are full of descriptive statements concerning the structure and mechanics of the middle and internal ears that are necessarily pertinent to any theory and are themselves the material of science. They can not all be listed separately, but we may indicate their general nature.

4. The kinematic analysis of the middle ear, and its conception as a mechanical system slung between opposing elastic tensions and operating under Hooke's law, at once provide valuable data regarding the actual dimensions and the probable displacements of parts.

5. The analysis of the inner ear is similarly informative. It is of exceptional value that we should know the hinge-like motion of the stapes,[41] the dimensions of the cochlea, the relative velocities of the lymph at various points, the size and relations of the various members of the organ of Corti at different regions of the cochlea, the probable displacement of the basilar membrane, the hinging of the arch of Corti, the relation of the tectorial membrane to the hairs, the kinematics of the organ of Corti that translates basilar displacement into transverse bending of the hairs,[42], the approximate amount of this displacement,[43] the elastic resistance of the tectorial membrane,[44] the lack of correspondence between the hair cells, the tectorial fibres and basilar fibres,[45] the peculiar properties of the vascular body,[46] and the other details of like

[40] Wrightson, pp. 21 f.; E. R. Jaensch, *Zeitschr. f. Sinnesphysiol.* **47,** 1913, 256 ff.
[41] Pp. 42 ff.
[42] Pp. 95-127.
[43] Pp. 189 ff.
[44] P. 209.
[45] P. 247.
[46] Pp. 181 f.

nature. The study of the inner ear of the sparrow shows that certain parts of the human ear are in all probability inessential to a discriminative hearing of tones.[47] The suggestion that the broadening of the basilar membrane toward the tip of the cochlea is a compensation for its less favorable situation is also worthy of notice.

All these facts are of great value, even though they have not as yet eventuated in a tenable theory. They belong to the observational half of science, and the primary half. If we had had more of them and fewer theories, we should know more; or rather, if we had had more of them, we should have fewer theories. Wrightson has given us no new theory, that shall "win the assent and support of physiologists, psychologists, physicists and musicians;" so far as that goes, the Helmholtz theory may continue to rest as comfortably as its intrinsic condition permits. But he has given us more facts than we have had for many a day.[48] And he has thus begun his scientific work where it should be begun,—with observation.

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[47] P. 228.

[48] Let it not be forgotten that Wrightson, when he lacked facts, sought out a competent preparator to make for him three series of microscopical sections of the human ear. See Appendix, p. 157.